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A Robust Sensorless Control of PMSM Based on Sliding Mode Observer and Model Reference Adaptive System

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ABSTRACT

This paper is intended to study and compare the operation of two methods for estimating the position/ speed of the permanent magnet synchronous motor (PMSM) under sliding mode control. The first method is a model reference adaptive system (MRAS). The second method based on sliding mode observer (SMO). The stability condition of Sliding Mode Observer was verified using the Lyapunov method to make sure that the observer is stable in converging to the sliding mode plane. In this paper the performances of the proposed two algorithms are analyzed using SIMULINK/MATLAB. The simulations results are presented to verify the proposed sensorless control algorithms and can resolve the problem of load disturbance effects by simulations which verify that the two closed-loop control system is robust with respect to torque disturbance rejection.

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1. INTRODUCTION

The permanent magnet synchronous motors attract the industrial world attention thanks to their superior advantages, for instance their higher efficiency, low inertia, high torque to current ratio. As an important application of PMSM, the motion control requires not only the accurate knowledge of rotor position for field orientation but also the information of rotor speed for closed-loop control; thus, position transducers such as optical encoders and resolvers are needed to be installed on the shaft [1],[2]. However, these sensors are expensive and very sensitive to environmental constraints such as vibration and temperature [3]. In order to overcome these problems, instead of using position sensors, a sensorless control method has been developed for control of the motor [4]. The basic principle of sensorless control is to deduce the rotor speed and position using various information and means, including direct calculation, parameter identification, condition estimation, indirect measuring and so on. The stator currents and voltages are generally used to calculate the information of speed and rotor position [5].

The sliding mode control has been used to improve the robustness of the controller. during the sliding mode, this controller is insensitive to parameter variations and disturbances [6]. Therefore, many approaches for speed estimation have been investigated in the literature [7]-[8].

This paper presents two methods for estimating the position and speed of a permanent magnet synchronous motor (PMSM) drive. The first method is Model Reference Adaptive System. It makes use of the redundancy of two machine models of different structures that estimate the same state variable (rotor speed) of different set of input variables [9]. The estimator that does not involve the quantity to be estimated is chosen as the reference model, and the other estimator may be regarded as the adjustable model. The error between the estimated quantities obtained by the two models is proportional to the angular displacement between the two estimated flux vectors. A PI adaptive mechanism is used to give the estimated speed [10]-[11]. The second method is Sliding Mode Observer, which is robust and easy to implement. The siding mode observer is built based on the mathematical model of PMSM under α-β coordinate system [11]. The performance of the proposed controller in verified by computer simulations.

2. THE PMSM NONLINEAR STATE MODEL

Considering the traditional simplifying assumptions, the synchronous permanent magnet machine can be elaborated by carrying out a modeling within the meaning of Park. The machine model in the turning dysphasic reference (d-q) is written [12]-[13]:

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ \omega \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_{sd}} i_{sd} + \frac{L_{sq}}{L_{sd}} \omega i_{sq} \\ -\frac{L_{sd}}{L_{sq}} \omega i_{sd} - \frac{R_s}{L_{sq}} i_{sq} - \frac{\phi_f}{L_{sq}} \omega \\ \frac{P^2}{J}\left(\left(L_{sd} - L_{sq}\right) i_{sd} i_{sq} + \phi_f i_{sq}\right) - \frac{F}{J}\omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{sd}} & 0 \\ 0 & \frac{1}{L_{sq}} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \tag{1}$$

Usually, this model (1) is used for the vector control design whereas, for the observer design, the model will be written in stationary reference frame frame (α-β) as the speed and the position information are ready to be extracted in this reference frame [6],[14]. Then the model can be written as follows:

$$\frac{d}{dt}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \omega \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} i_{s\alpha} + \frac{\phi_f}{L_s} \omega \sin\theta \\ -\frac{R_s}{L_s} i_{s\beta} - \frac{\phi_f}{L_s} \omega \cos\theta \\ \frac{P^2}{J} \phi_f \left(i_{s\beta} \cos\theta - i_{s\alpha} \sin\theta\right) - \frac{F}{J}\omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} \tag{2}$$

3. SLIDING MODE CONTROL OF PMSM

3.1. Design of the Sliding Mode Control (SMC)

The design of the SMC takes into account the problems of stability and good performance in a systematic way in its approach [9],[15]. In general, for this type of control, three steps must be performed: Chose the sliding surface, Determination of existence conditions plan or slippery conditions of access, Synthesis control laws of sliding mode.

3.2. The Speed Control of PMSM

Adjusting the speed of PMSM requires monitoring the current consumed by the motor. A conventional solution is to use the principle of cascade control method of the inner loop enables the current control, of the outer loop to control the speed [8],[9]. The first surface speed that is written by:

$$S(\Omega) = \Omega_{ref} - \Omega \tag{3}$$

During the sliding mode and the steady state, we have:

$$S(\Omega) = 0 \;\; and \;\; \dot{S}(\Omega) = 0 \tag{4}$$

Hence we deduce:

$$i_{sqeq} = \frac{F\Omega + C_r}{P[\phi_f - (L_{sd} - L_{sq}) i_{sd}]} \tag{5}$$

with: $i_{sqn} = K_{\Omega} sign(S(\Omega))$. Thus, the control i_{sqref} represents the sum of magnitudes i_{sqeq} and i_{sqn}:

$$i_{sqref} = i_{sqeq} + i_{sqn} \tag{6}$$

3.3. The Current Control of PMSM

The second surface of the inner loop accountable for controlling the current i_{sq} is described by:

$$S(i_{sq}) = i_{sqref} - i_{sq} \tag{7}$$

The derivative of the surface is given by:

$$S(\dot{i}_{sq}) = \frac{R_s}{L_{sq}} i_{sq} + \frac{L_{sd}}{L_{sq}} \omega i_{sd} + \frac{\phi_f}{L_{sq}} \omega - \frac{1}{L_{sq}} V_{sq} \tag{8}$$

During the sliding mode and the steady state, we have:

$$S(i_{sq}) = 0 \quad and \quad S(\dot{i}_{sq}) = 0 \tag{9}$$

Hence we deduce:

$$V_{sqeq} = R_s i_{sq} + L_{sd} \omega i_{sd} + \phi_f \omega \tag{10}$$

with: $V_{sqn} = K_{isq} sign(S(i_{sq}))$. Thus, the control V_{sqref} represents the sum of magnitudes V_{sqeq} and V_{sqn}:

$$V_{sqref} = V_{sqeq} + V_{sqn} \tag{11}$$

The third surface is that of the current control i_{sd}. It is described by:

$$S(i_{sd}) = i_{sdref} - i_{sd} \tag{12}$$

The derivative of the surface is given by:

$$S(\dot{i}_{sd}) = \frac{R_s}{L_{sd}} i_{sd} - \frac{L_{sq}}{L_{sd}} \omega i_{sq} - \frac{1}{L_{sd}} V_{sd} \tag{13}$$

During the sliding mode and the steady state, we have:

$$S(i_{sd}) = 0 \quad and \quad S(\dot{i}_{sd}) = 0 \tag{14}$$

Hence we deduce:

$$V_{sdeq} = R_s i_{sd} - L_{sq} \omega i_{sq} \tag{15}$$

with: $V_{sdn} = K_{isd} sign(S(i_{sd}))$. Thus, the control V_{sdref} represents the sum of magnitudes V_{sdeq} and V_{sdn}:

$$V_{sdref} = V_{sdeq} + V_{sdn} \tag{16}$$

4. MRAS SENSORLESS SPEED CONTROL

In this method there is a reference model and an adjustable model. The first model is used to determine the required states and the second model is an adaptive model which is used to provide the estimated values of the states [16]-[17]. The difference between the output of these two models are fed to an adaptation mechanism to estimate the adjustable parameters that tunes the adaptive model in such a way that drives the error between these two models to zero Figure 1.

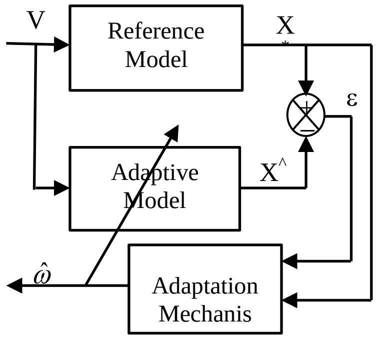

Figure 1. Structure MRAS for the estimate speed

The state space d-q axis stator currents of PMSM designed as reference model is given by:

$$\begin{bmatrix}\dot{i}_{sd}\\ \dot{i}_{sq}\end{bmatrix}=\begin{bmatrix}-\frac{R_s}{L_{sd}} & \omega\frac{L_{sq}}{L_{sd}}\\ -\omega\frac{L_{sd}}{L_{sq}} & -\frac{R_s}{L_{sq}}\end{bmatrix}\begin{bmatrix}i_{sd}\\ i_{sq}\end{bmatrix}+\begin{bmatrix}\frac{1}{L_{sd}} & 0\\ 0 & \frac{1}{L_{sq}}\end{bmatrix}\begin{bmatrix}V_{sd}\\ V_{sq}\end{bmatrix}+\begin{bmatrix}0\\ -\omega\frac{\phi_f}{L_{sq}}\end{bmatrix} \tag{17}$$

The state space d-q axis stator currents of PMSM designed as adjustable model is given by:

$$\begin{bmatrix}\dot{\hat{i}}_{sd}\\ \dot{\hat{i}}_{sq}\end{bmatrix}=\begin{bmatrix}-\frac{R_s}{L_{sd}} & \hat{\omega}\frac{L_{sq}}{L_{sd}}\\ -\hat{\omega}\frac{L_{sd}}{L_{sq}} & -\frac{R_s}{L_{sq}}\end{bmatrix}\begin{bmatrix}\hat{i}_{sd}\\ \hat{i}_{sq}\end{bmatrix}+\begin{bmatrix}\frac{1}{L_{sd}} & 0\\ 0 & \frac{1}{L_{sq}}\end{bmatrix}\begin{bmatrix}V_{sd}\\ V_{sq}\end{bmatrix}+\begin{bmatrix}0\\ -\hat{\omega}\frac{\phi_f}{L_{sq}}\end{bmatrix} \tag{18}$$

After developing adjustable and reference models, the adaptation mechanism will be built for MRAS method. The adaptation mechanism is designed in a way to generate the value of estimated speed used so to minimize the error between the estimated and reference d-q axis stator currents. The error between the estimated and reference d-q axis stator currents are defined as:

$$\begin{cases}\varepsilon_d = i_{sd} - \hat{i}_{sd}\\ \varepsilon_q = i_{sq} - \hat{i}_{sq}\end{cases} \tag{19}$$

The state currents error component is:

$$\begin{bmatrix}\dot{\varepsilon}_d\\ \dot{\varepsilon}_q\end{bmatrix}=\begin{bmatrix}-\frac{1}{\tau_d} & \hat{\omega}\frac{L_{sq}}{L_{sd}}\\ -\hat{\omega}\frac{L_{sd}}{L_{sq}} & -\frac{1}{\tau_q}\end{bmatrix}\begin{bmatrix}\varepsilon_d\\ \varepsilon_q\end{bmatrix}+\begin{bmatrix}\frac{L_{sq}}{L_{sd}}i_{sq}\\ -\frac{L_{sd}}{L_{sq}}i_{sd}-\frac{\phi_f}{L_{sq}}\end{bmatrix}\left(\omega-\hat{\omega}\right) \tag{20}$$

Using Equation (20), the state error model of the PMSM in the d-q synchronous reference frame is given as flow:

$$\left[\overset{\bullet}{\varepsilon}\right]=[A][\varepsilon]+[W] \tag{21}$$

Where $[\varepsilon]=\left[\varepsilon_d \quad \varepsilon_q\right]^T$ is the error state vector,

$[W]=\begin{bmatrix} \dfrac{L_{sq}}{L_{sd}}i_{sq} \\ -\dfrac{L_{sd}}{L_{sq}}i_{sd}-\dfrac{\phi_f}{L_{sq}} \end{bmatrix}\left(\omega-\hat{\omega}\right)$ is the output vector of the feedback block.

The mechanical time constant is too much bigger than the electrical time constant, hence the parameter □□in A can be considered as linear time invariant parameter, the feedback used by adaptive mechanism is nonlinear time varying feedback [18]-[19]. Where □ is the input and the error [□] is the output of the linear feed forward block whose transfer function is H(S)=(S[I]-A])$^{-1}$. For stability of MRAS there are two conditions, the first: H(S) must be always strictly positive real [20], the second: the nonlinear time varying block must fulfil Popov's hyper stability criterion [21]. The first condition can be achieved by making sure that all the poles of H(S) have negative real parts. The second condition can be achieved by:

$$\int_0^{t_1}[\varepsilon]^T[W]dt \geq -\gamma^2 \text{ in which, } \forall\, t_1 \geq 0, \tag{22}$$

□□□is a finite positive constant independent of t_1.

By using the Popov's theory, the system of the MRAS speed estimation is asymptotically stable. Finally, from (21), we can conclude that the observed rotor speed satisfiers the following adaptation laws:

$$\hat{\omega}=\left(A_1+\frac{A_2}{S}\right) \tag{23}$$

$$A_1=K_{p\hat{\omega}}\left[-\frac{L_{sq}}{L_{sd}}i_{sq}\varepsilon_d-\left(\frac{L_{sd}}{L_{sq}}i_{sd}+\frac{\phi_f}{L_{sq}}\right)\varepsilon_q\right]$$

Where $A_2=K_{i\hat{\omega}}\left[-\frac{L_{sq}}{L_{sd}}i_{sq}\varepsilon_d-\left(\frac{L_{sd}}{L_{sq}}i_{sd}+\frac{\phi_f}{L_{sq}}\right)\varepsilon_q\right]$; $K_{p\hat{\omega}}$ *and* $K_{i\hat{\omega}}$ are the PI speed observer controller.

A PI adaptive mechanism is used to give the estimated speed. As the error signal gets minimized by the PI. The rotor estimated speed is generated from the adaptation mechanism using the error between the estimated and reference currents obtained by the model as follows:

$$\hat{\omega}=\left(K_{p\hat{\omega}}+\frac{K_{i\hat{\omega}}}{S}\right)\left[-\frac{L_{sq}}{L_{sd}}i_{sq}\varepsilon_d-\left(\frac{L_{sd}}{L_{sq}}i_{sd}+\frac{\phi_f}{L_{sq}}\right)\varepsilon_q\right] \tag{24}$$

Finally, the estimated rotor position is obtained by integrating the estimated rotor speed.

$$\hat{\theta} = \frac{1}{S}\hat{\omega} \tag{25}$$

5. SENSORLESS SPEED CONTROL ASSOCIATED WITH SLIDING MODE OBSERVER(SMO)

The sliding mode observer is based on a stator current estimator as the stator currents and voltages are the only measured states in a PMSM drive system [14],[22]-[23]. Then a sliding mode observer can be designed as follows:

$$\begin{cases} \dot{\hat{i}}_{s\alpha} = -\frac{R_s}{L_s}\hat{i}_{s\alpha} + \frac{P\phi_f}{L_s}\hat{\Omega}\sin(\hat{\theta}) + \frac{V_{s\alpha}}{L_s} + K_1 sign(\overline{i_{s\alpha}}) \\ \dot{\hat{i}}_{s\beta} = -\frac{R_s}{L_s}\hat{i}_{s\beta} - \frac{P\phi_f}{L_s}\hat{\Omega}\cos(\hat{\theta}) + \frac{V_{s\beta}}{L_s} + K_1 sign(\overline{i_{s\beta}}) \\ \dot{\hat{\Omega}} = \frac{\hat{C}_{em} - C_r - F\hat{\Omega}}{J} + K_2\left(sign(\overline{i_{s\alpha}}) + sign(\overline{i_{s\beta}})\right) \end{cases} \tag{26}$$

With: $\overline{i_{s\alpha}} = i_{s\alpha} - \hat{i}_{s\alpha}$ $\overline{i_{s\beta}} = i_{s\beta} - \hat{i}_{s\beta}$ and K_1, K_2 are the observer gains. The Equations of dynamic errors are:

$$\begin{cases} \dot{\overline{i_{s\alpha}}} = -\frac{R_s}{L_s}\overline{i_{s\alpha}} + \frac{P\phi_f}{L_s}\left(\Omega\sin(\theta) - \hat{\Omega}\sin(\hat{\theta})\right) - K_1 sign(\overline{i_{s\alpha}}) \\ \dot{\overline{i_{s\beta}}} = -\frac{R_s}{L_s}\overline{i_{s\beta}} - \frac{P\phi_f}{L_s}\left(\Omega\cos(\theta) - \hat{\Omega}\cos(\hat{\theta})\right) - K_1 sign(\overline{i_{s\beta}}) \\ \dot{\overline{\Omega}} = \frac{\overline{C_{em}} - F\overline{\Omega}}{J} - K_2\left(sign(\overline{i_{s\alpha}}) + sign(\overline{i_{s\beta}})\right) \end{cases} \tag{27}$$

With: $\overline{\Omega} = \Omega - \hat{\Omega}$, $\overline{C_{em}} = C_{em} - \hat{C}_{em}$

The analysis of the observer convergence will be carried out using the following Lyapunov function:

$$V = \frac{1}{2}\left(\overline{i_{s\alpha}}^2 + \overline{i_{s\beta}}^2 + \overline{\Omega}^2\right) \tag{28}$$

Its derivative is:

$$\begin{aligned} \dot{V} &= \overline{i_{s\alpha}}\,\dot{\overline{i_{s\alpha}}} + \overline{i_{s\beta}}\,\dot{\overline{i_{s\beta}}} + \overline{\Omega}\dot{\overline{\Omega}} + \overline{\theta}\dot{\overline{\theta}} \\ &= -\frac{R_s}{L_s}\overline{i_{s\alpha}}^2 + \frac{P\phi_f}{L_s}\overline{i_{s\alpha}}\left(\Omega\sin(\theta) - \hat{\Omega}\sin(\hat{\theta})\right) - K_1\left|\overline{i_{s\alpha}}\right| \\ &\quad - \frac{R_s}{L_s}\overline{i_{s\beta}}^2 - \frac{P\phi_f}{L_s}\overline{i_{s\beta}}\left(\Omega\cos(\theta) - \hat{\Omega}\cos(\hat{\theta})\right) - K_1\left|\overline{i_{s\beta}}\right| \\ &\quad + \frac{\overline{C_{em}}\,\overline{\Omega} - F\overline{\Omega}^2}{J} - K_2\overline{\Omega}\left(sign(\overline{i_{s\alpha}}) + sign(\overline{i_{s\beta}})\right) \end{aligned} \tag{29}$$

With $\left|\overline{i_{s\alpha}}\right| = \overline{i_{s\alpha}}\,sign(\overline{i_{s\alpha}})$ *and* $\left|\overline{i_{s\beta}}\right| = \overline{i_{s\beta}}\,sign(\overline{i_{s\beta}})$

To guarantee the convergence, the time derivative of the candidate Lyapunov function is forced Such that. $\dot{V} < 0$. Knowing that [4], [14], [22]:

$$\left|\Omega\sin(\theta) - \hat{\Omega}\sin(\hat{\theta})\right| \langle 2\Omega_{\max} \tag{30}$$

$$\left|\overline{i_{s\alpha}}\right| = \left|\overline{i_{s\beta}}\right| \langle 2i_{\max} \tag{31}$$

$$-\frac{R_s}{L_s}\overline{i_{s\alpha}}^2 \langle 0, \quad \frac{P\phi_f}{L_s}\overline{i_{s\beta}}^2 \langle 0 \quad and \quad \frac{F}{J}\overline{\Omega}^2 \langle 0 \tag{32}$$

thus, the gains will be tuned such as:

$$K_1 \rangle \left|\frac{P\phi_f}{L_s} 4\Omega_{\max}\right| \tag{33}$$

$$K_2 \rangle \left|2i_{\max}\right| \tag{34}$$

Based on analysis of the aspects mentioned above, Figure 2 shows the block diagram of the sensorless control of PMSM. We take $u_{\alpha\beta}$, $i_{\alpha\beta}$ as input of the Sliding Mode Observer and u_{dq}, i_{dq} as input of the Model Reference Adaptive System.

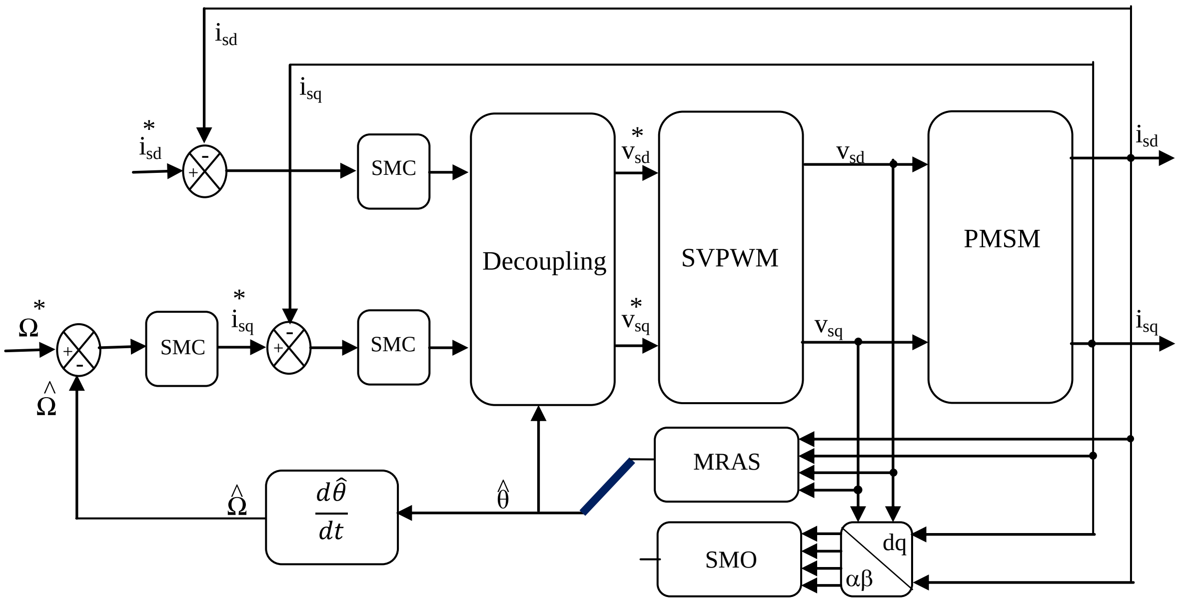

Figure 2. Block diagram of Sensorless Vector Control of PMSM

6. SIMULATIONS RESULTS

To demonstrate the performance of the proposed control scheme, a set of simulations is carried out on a PMSM model by using SIMULINK/MATLAB. The parameters of the tested *PMSM* are given in Table 1. In this section, the speed setting is treated with the sliding mode control mode associated with the PMSM two Observers Sliding Mode Observer, Model Reference Adaptive System powered by a voltage inverter with PWM control. The speed reference trajectory is given by the following benchmark: (0, +100, -100, 0) rad/s.

Figure 3 and 4 show all sizes estimated by two observers (*SMO, MRAS*). It is found that the estimated values show a transient without overshoot. We note that the response of the estimated speed is similar to that measured following the reference speed with almost zero error and validated the robustness of the sensorless Sliding Mode Control associated with the two observers.

Figure 5 and 6 show an observation error between the actual speed and the estimated speed. We can see that the estimation error is very small. This result attests the good estimation on the speed. The sliding Mode Observer has superiority and gives the best performance and robustness at the startup overshoot and overshoot of the load application relative to the *MRAS* observer as shown in Table 2. The currents in the sliding control show a good response time according to the *d* and *q* axes currents references with or without load as shown in Figure 7. It illustrates the performance and the robustness of the control sensorless sliding mode with these observers.

Table 1. Parameters of the Motor

Components	Values	Units
C_n	5	Nm
Ω_n	1000	t_r/min
R_s	1.67	Ω
L_s	1.45	mH
P	3	-----
ϕ_f	0.17	Wb
J	3.10^{-4}	$Kg.m^2$
F	0.013	Nm/rad/s

Table 1. Summary of proposed control simulation performance

Observers	D_d *(%)*	T_r *(ms)*	T_m (ms)	E_s *(%)*	D_p *(%)*	*Tp (ms)*
MRAS	0.018	50,03	40,1	0	0.45	2
SMO	0.007	50,04	40,1	0	0,34	1,2

D_d (%)	The overshoot at startup
D_p (%)	The overshoot for load application
T_r (ms)	The response time
T_m (ms)	The rise time
E_s (%)	The static error
T_p (ms)	The load rejection time
V_{sd}, V_{sq}	Stator winding d, q axis voltage respectively
i_{sd}, i_{sq}	Stator winding d, q axis current respectively
i_{sd}^*, i_{sq}^*	Reference stator winding d, q axis current respectively
Ω	The electric rotor speed
Ω^*	Reference rotor speed
$\hat{\Omega}$	Estimated rotor speed
θ	Rotor position
ϕ_f	Permanent Magnet Flux
R_s	Stator phase resistance
L_{sd}, L_{sq}	The stator inductances of the axis d, q
J	Inertia of turning parts
F	Viscous friction coefficient
P	Poles pairs number
C_r	Load torque

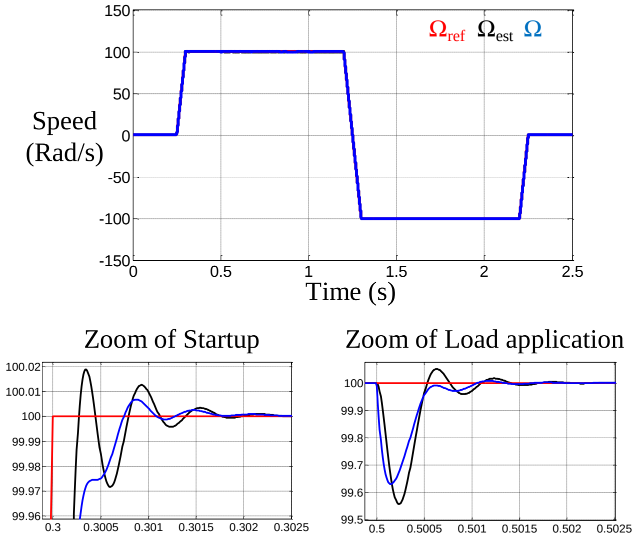

Figure 1. The rotational speed (Real, Estimated, Reference) in the control sliding mode based on MRAS

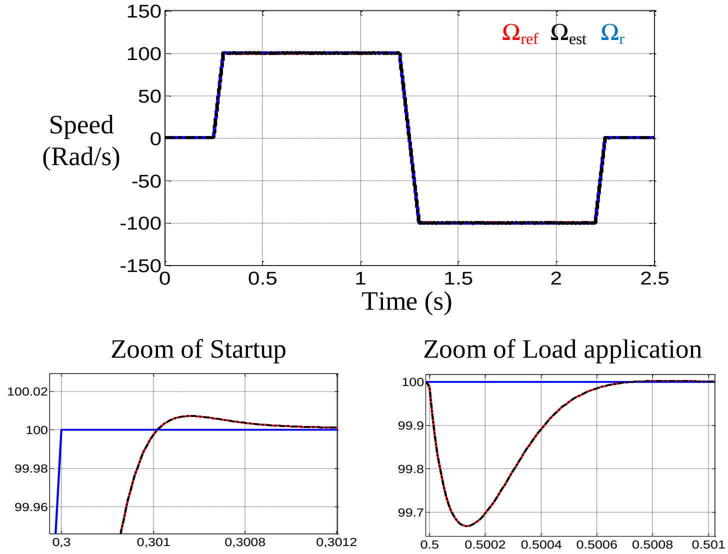

Figure 2. The rotational speed (Real, Estimated, Reference) in the control sliding mode based on SMO

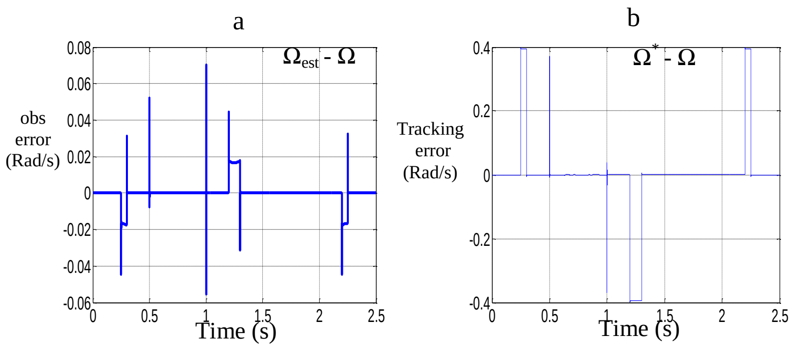

Figure 5. a) Observed speed error, b) Tracking speed error in the control sliding mode based on MRAS

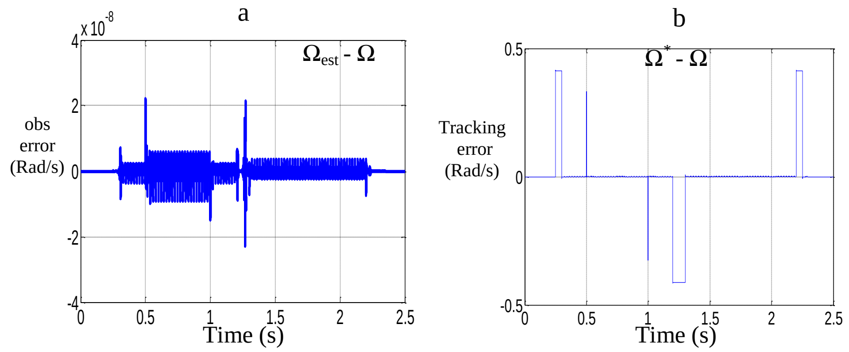

Figure 6. a) Observed speed error b) Tracking speed error in the control sliding mode based on SMO

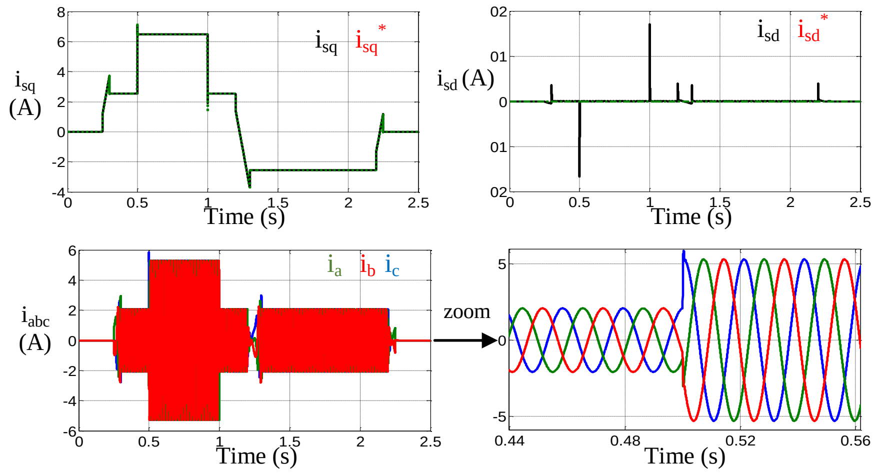

Figure 7. Simulation results: measured i_{sq}, measured i_{sd}, measured phase stator current

7. CONCLUSION

A robust control sensorless of a permanent magnet synchronous motor is presented. The simulation results obtained in this work confirm its feasibility and validate excellent dynamic performance. The results show a good estimation under different operating conditions and low sensitivity to external disturbances they allowed us to get rid of especially mechanical speed sensor or position, which is expensive and fragile. Concluded against that both Sliding Mode Observer and Model Reference Adaptive System are simple to implement, don't take into account the measurement noise or the environment. They not require a long calculation time, and have a good dynamic response speed and good disturbance rejection; they show a response time and efficient robustness. According to the simulation results the Sliding Mode Observer has a superiority and gives the best performance and robustness relative to the Model Reference Adaptive System of sensorless sliding mode control in terms of low speed behavior, speed reversion and load rejection. Therefore, future work will focus on experimental validation using test bench to verify the proposed methods.

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